AN IMPROVED PLUGGING SYSTEM FOR HX TUBING

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Abstract

Extensive technical analysis and a comprehensive testing program have identified the important parameters and changes needed for an improved tube plugging system. The new plugging system is specifically aimed to perform successfully in the severe operating conditions found in high pressure heat exchangers. There are two important components of the new system. The first is a new plug with improved gripping and sealing capability. The second is a simple procedure for preparing and sizing tubes to obtain successful plug installation.

The technical analysis and testing were facilitated by electronic measuring and computer recording means. The testing system utilized high temperature ovens, band heaters to create thermal cycling effects, vibration and shock generation, and high pressure systems capable of generating pressures in excess of 20,000 psi. Tests have been conducted on well over 1000 plugs.

Experience at the Davis-Besse Nuclear Power Station has shown that the new generation plugging system is substantially less costly than welded plugs. More than 72 of these new plugs could be installed in a single shift. In comparison, the welded plug required an experienced welder to spend the same time to install fifteen plugs. Savings, as compared to using explosively welded plugs, have also been recorded at other power stations.

Introduction

The Davis-Besse Nuclear Power Plant, powered by a single B&W PWR reactor with a capacity of 874 net Mwe, began commercial operation in July of 1978. This plant, owned and operated by Toledo Edison, is experiencing leaks in their feedwater heaters, typical of many nuclear and fossil plants. It was first determined that welded tube plugs provided the best permanent repair, particularly for high pressure heaters. However, welding is also expensive and time consuming. As few as fifteen plugs could be welded in a single shift. Successful welding requires time for careful preparation to enlarge and properly clean the tube in addition to the weld.

An alternative plugging solution was presented to Davis-Besse in 1994. A new mechanical tube plug design, the P2 Pop-A-Plug®, was developed to combine the permanence of a welded plug with speed and ease of installation. This plug is manufactured by Expansion Seal Technologies, a division of EST Group, Inc. One of the features of this new product is the simplified installation system. When the P2 plugs were first used by Davis-Besse maintenance personnel in October 1994, more than 72 plugs were installed in a single shift. The total savings for this one outage, in which 290 plugs were installed, were in excess of $5,000.

Background

There are many different ways of plugging leaking heat exchanger tubes. They range from expensive means such as explosive plugs or welded pins, through moderate cost plugs using elastomer or expanded metal seals, to the inexpensive tapered pin that is hammered into the tube.

Explosive plugs are used primarily in high pressure heat exchangers because of their high cost. They must be installed by a person certified to handle explosives, usually available only through a contractor. Permits may be required. The contractor must carefully prepare and clean the tube. The explosive plug is thimble shaped and packed with an explosive charge. Cleanliness is very important as contaminants will prevent the plug and tube from coming as close to each other as required during the explosion to effect a good bond. The weld is not a fusion weld as there is not enough heat generated to melt the metals. The joint is a result of the two materials being forced so hard against each other that they bond together. As long as contamination is not present, the joint strength exceeds the weakest material. The thimble shape is very important as it relieves the very large stresses that would otherwise occur because of substantial differential expansion due to the different materials involved. Adjacent tubes must be packed to prevent cracked ligaments and damage to adjacent tube-to-sheet joints unless the tube pitch to diameter ratio exceeds 1.7 or 1.8. This is among the most expensive methods, because of the high cost of both the plug and a certified technician to prepare the tube, protect the surrounding tubes, and install the plug safely. There is also a very high cost to the Utility in down time of the heat exchanger.

Welding of tapered pins or thimble plugs to tubes also requires extreme cleanliness and a skilled welder to make a leak tight weld. The stresses, from welding, may not be confined to a small area because heat flows easily to the surrounding metal. When the molten metal solidifies and contracts, stresses pull on the tube sheet ligament and adjacent tube to sheet joints. These stresses increase with the amount of heat and the molten metal volume and can cause damage to the ligament or adjacent tubes either immediately after the welding or at a later date. Cases have been recorded where welded pins, which appeared sealed after installation, later began to leak as a result of thermal cycling pulling apart the weld joint. Thimble shaped welded plugs are more reliable because they relieve stress at the weld joint. The installed cost of welded plugs and the economic losses from down time are very high. However, they are considered the most reliable method by many experts.

Lower cost elastomer seals, are not able to retain a tight seal because they lose their resilience with age and heat exchanger operating temperatures. The least expensive method, hammered in tapered pins, seal only at the end of the tube. The pin must be struck hard enough to distort the end of the tube because the tube never has a perfectly flat edge or round hole due to distortion from welding or erosion. The ligament or adjacent tube seals can be damaged, because of the necessary tube distortion, resulting in later expensive repair. There is no way of knowing how hard the pin must be struck to effect a seal and at the same time not damage the adjacent tubes. Furthermore, because the sealing surface approaches line contact, it may easily be loosened if struck sideways by a falling tool or an errant hammer blow. Loosened pins may be accidentally exploded outward against an unsuspecting maintenance person. Figure 1 shows the damage to a 1/2 inch thick Plexiglas plate caused by an exploding pin. This can occur during pressure test or be due to a pressure trapped in the tube. This unsafe situation has resulted in serious injury on more than one occasion. European industry is far ahead of the USA in protecting the lives of maintenance workers by moving away from the use of hammered in tapered pins.

Other moderate cost solutions expand a metal ring to seal against the tube ID. This is done by hammering a tapered pin through a ring to expand the ring. Another method uses threaded engagement to pull a tapered pin through the ring. Both are improvements over the hammered in tapered pin because they seal against the tube ID. However, the installer can still install the plug with too little force to seal or a large enough force to cause damage to the adjacent tubes.

There is one plug design that, independently of any operator action, limits the forces placed upon the tube sheet and adjacent tubes to protect them from damage. This is accomplished through the use of a tension limiting member, called a breakaway, that "pops" and limits the maximum force with which a metal ring can be forced against a tube ID. Figure 2 illustrates the original PRP series of the Pop-A-Plug®[1] design. A hydraulic ram, not shown, is shouldered against the plug positioner and draws the pull rod to the right, expanding the ring until it seals against the tube. The breakaway fractures at its reduced cross-section before the ligaments or adjacent tubes can be damaged.

However, the success of any plug installation depends upon more than avoiding damage to the ligament or adjacent tubes. The earlier Pop-A-Plug® design, called the PRP series, had several important drawbacks. It had a very narrow window of installation that was between 0.007 and 0.016 inches smaller than the tube. Therefore it was often undersized or oversized resulting in a leak or ejected plug. It had limited squeeze into the tube which limited it's ability to handle pressure. Heavy lubricants, which were required to control the friction between the pin and the ring, introduced undesirable variability. There was no good method for preparing or measuring the tube.

An extensive review, development, and testing program was undertaken to obtain reliable sealing by improving upon the basic idea of the Pop-A-Plug ®. This led to a new system of plugging which is both simple to execute and superior in sealing. The development goal was to obtain as reliable long term performance as welded or explosive plugs in high pressure heat exchangers at a fraction of their installed cost.

Goals for the New Plugging System

The design goals for an ideal plugging system are:

1. The plug must perform reliably over the life of the heat exchanger under the most severe conditions.
2. The plug installation system must be simple, quick, and reliable. The installer must not be required to have special skills. Plant maintenance personnel should be able to install the plug easily by following a few simple instructions. Correct sizing of the plug must be simple and foolproof. Preparation of the tube, sizing, and installation of the plug should require only a few minutes using simple tools.
3. The installation of the plug must not cause damage to adjacent tubes no matter what the operator does.
4. The plug must be safe for all maintenance workers.
5. The installed cost of the plug must be lower than explosive or welded plugs.

Installation Problems and Solutions

The first problem for any plugging system is PLUG SIZING. No known plugging system has a "one-size-fits-all" capability. If the plug is too small, it cannot be expanded enough to install the plug, or if it can be installed, it will leak or blow out at a low pressure. Basically, we must use the largest plug that will fit into the prepared tube hole. Each plug must work perfectly over a tube size range larger than the difference in available plug sizes.

Some heat exchangers employ different tube sizes or different wall thickness all within one tube bundle. Even if all tubes in a heat exchanger are one size, their actual ID's may vary considerably for a number of reasons. Foremost of these is erosion at the inlet end from fluid turbulence. The author has seen as much as 0.047 inches wall erosion in a thirty year old heater. Additional factors are variations in the tube sheet holes, the amount of wall reduction from rolling, and the tubes themselves. Selecting the plug size on the basis of the published tube dimensions, even if the effect of rolling is accounted for, will often lead to using undersized plugs and an improper installation.

Therefore, a first requirement is that the installation system must make it easy for the installer to accurately determine the correct size of plug to use in a prepared tube.

The number two problem is the ability of the plug to SEAL DEFECTS IN THE TUBE. Heat exchanger tubes are typically pitted and severely eroded by corrosion and fluid turbulence. The tube ID's may be out-of-round which increases the difficulty of sealing. Weld projection at the tube inlet will occur because the harder weld nugget erodes more slowly than the softer tube. This projection can prevent the installer from using the proper plug size.

No plug, designed to seal against the tube ID, can be installed without any tube preparation and be counted upon to provide a reliable seal. Tube defects must be corrected to get a good seal. However, no tube surface can be made perfect. We can imagine that the application of a greater sealing force will seal any surface imperfection by deforming it or the plug. Why can't we use a higher compressive force to accomplish sealing? Heat exchangers are made with thin ligaments to minimize size and cost. Therefore, if we are to prevent ligament and adjacent tube damage, we must limit the force used to seal a plug against a tube. In turn this requires that we properly prepare the tube to be able to make the plug seal with forces that will not damage the ligament or adjacent tubes.

Summarizing what we have learned: **In order to have a successful installation the tube must be prepared to eliminate defects and the correct size of plug must be determined by accurately measuring the tube.**

It turns out that the sizing problem and tube preparation problem are interrelated. If we first remove any projection at the inlet we can use a very simple "go-no go" gage to determine the correct size of plug to use. The correct size of plug is the largest plug that will fit into the prepared tube hole. Figure 3 shows the "go-no go" gage with the "go" end inserted into the tube. The "go" end is the same size as the associated plug. The "no go" end is the size of the next largest plug. Therefore, if the “go” end fits and the “no go” end does not, the plug size marked on the gage is the largest plug that will fit in the tube hole. Alternately we could use the plug itself to determine the largest plug that would fit into the prepared hole. However, using the plug itself as a gage would possibly damage the outer serrations and interfere with good sealing.

The "go-no go" concept is much simpler to use than calipers, snap gages or ball micrometers as the latter require a skill usually associated with persons who are qualified to be machinists or inspectors. The "go-no go" gage concept takes care of the requirement for simply and reliably determining the correct plug size.

The previously mentioned erosion problem at the tube inlet is depicted in Figure 4. This projection must be removed if we are to accurately measure the tube ID and to permit the correct plug size to pass beyond the narrowed inlet. The projection may be easily removed using a tapered reamer. Because of the taper, this reamer will not scar the tube ID if aligned with the tube within a half angle of the reamer.

The ideal method of preparing the tube ID is to use a wire brush designed and manufactured to act like a fly cutter. The brush is operated by a power drill. It must be moved back and forth in the tube to prevent causing a tapered condition in the tube. Tests show that the brush accomplishes several important objectives. These are:

1. In approximately thirty seconds of brushing, enough metal is removed to enlarge the tube to a diameter that is within a few thousandths of the brush diameter.
2. the brush acts to reduce any out-of-round condition.
3. the brush removes pitting marks.
4. the brush creates a ridged surface condition which provides a better grip between the plug and tube.
5. The brushing operation is simple and can be done by anyone with a minimum of training

The effective use of the brush requires that any weld projection first be removed with a tapered reamer and the proper size brush be selected. The proper brush size is the smallest brush that interferes with the hole after the weld projection has been removed. If a smaller brush is used it will not readily remove imperfections. On the other hand if a brush larger is used, it will be hard to insert in the tube and the bristles will be bent excessively preventing them from acting as fly cutters. Because of this the larger brush will not cut as effectively as a properly sized brush. The first brush may not remove all the tube imperfections. This is especially true if a drill, which has been used to remove a tapered pin or inlet sleeve, has made a deep scar in the tube. In such a case, after brushing for about 30 seconds the next larger brush may be employed and so on until all the tube defects have been removed.

Figure 5 shows how the tube size increases with brushing time. At the start of this experiment, the brush was only 0.010 inches larger than the tube. Material removal occurs rapidly until the hole approaches the brush size after which the size increases only slowly. Therefore it is possible to size the hole accurately for the intended plug but only if the correct size of brush is first used. The brush works effectively because the bristles are harder than the tube material and only if the bristles are not bent excessively.

Figure 6 shows the result of brushing for short periods with successively larger brushes to rapidly enlarge the tube ID by several plug sizes.

This method is far superior to drilling or reaming with an adjustable reamer. Adjustable reamers, operated manually, require great care to remove material slowly. Because they cut along the entire length of the flutes and because the flutes are not all the same diameter, they very readily scar and gouge the tube causing a greater problem. Other brushes that have been used to prepare tubes acted only to polish the tube because they were not constructed to act as fly cutters.

The procedure using the "go-no go" gage and special wire brush makes it possible to prepare the tube easily and quickly with a minimum of training and skill. The graphs of Figures 5 and 6 show how quickly material is removed. Figure 5 also shows that the rate at which the tube is enlarged approaches a limit as the hole size approaches the brush OD. This is an important feature because the brush acts like a drill in sizing the hole.

Design of a New Improved Plug

We have seen from the previous discussion that, even after proper plug sizing and proper tube preparation, it is important to be able to reliably seal remaining defects in the tube with a force less than that which would damage adjacent tubes. In order to accomplish this we must be able to expand the ring so that it is squeezed into any remaining tube defects. We can measure the ability of a plug to squeeze into defects and reliably seal by using the test apparatus of Figure 7. This apparatus measures the stroke of the pin, using a LVDT, and the force acting on the pin, using a pressure transducer to monitor the hydraulic ram pressure. Typical data from actual testing is plotted in Figure 8.

There are four different regions in Figure 8a which shows a plug being installed in a tube whose ID is much larger than the initial plug OD. The first and second regions show the rapidly rising force accompanying the initial elastic deformation of the ring and the transition from elastic to total plastic deformation. Region 3 shows the more gradually increasing force required to expand the ring plastically until the ring OD first touches the tube ID. Region 4 is the most important as it shows the travel of the pin from the point where the ring first touches the tube until the breakaway "pops". The fourth region travel is very important because it tells how much the outer serrations of the ring are being squeezed against the tube. The squeeze of the ring into the tube increases with travel in the fourth region. It is obvious that the third region force level must be low in order to get the greatest fourth region travel and consequent squeeze.

Figure 8b shows what happens when the tube ID is close to the initial size of the plug OD. In this case the ring first contacts the tube after a very brief third region pin travel as compared to Figure 8a. Again if we are to obtain the same squeeze for both a closely sized tube and a larger tube, the third region force must be low in relation to the breakaway force.

It was found that internal serrations shown in the patented P2 plug[2] design of Figure 9 reduce the third region force. This design also shapes the ring so that it acts to sweep away any debris on the pin thus preventing it from being caught between the pin and the ring. This acts to prevent galling between the pin and ring.

The final measure of performance is the ability of the plug to seal and withstand high pressures. No leakage has been found on thousands of Plugs experimentally tested with shop air and water at pressures to 10,000 psi. Plugs of this design were also tested with an Edwards helium leak detector capable of measuring leak rates as low as 10^{-10} cc/sec using a test set up of Figure 10. This arrangement is capable of measuring the true leak rate past the plug. All thirty plugs tested in this fashion showed no detectable sign of leakage using the most sensitive leak detector scale.

Other tests are routinely run to increase the pressure across the plug until it is ejected from the tube. This is done using the test set-up shown in Figure 11 that is limited to slightly over 20,000 psi. Results of testing carbon steel plugs with the test coupons prepared by power brushing are shown in Figure 12. Figure 12 shows performance in several popular sizes for high pressure heat exchanger tubes as well as the effect of the initial clearance between the plug OD and tube ID. It is seen from this data that the plugs will perform well beyond the 0.020 size range permitted by the "go-no go" gage system. If the "no go" end of the gage will not enter the tube, the tube is less than 0.020 inches larger than the plug. If the user neglects to measure the tube and accidentally installs an undersize plug, the plug positioner will become jammed against the pin or the breakaway will fracture on the wrong side of the collar. Both of these mishaps are identified in Figure 13. Either of these two events should warn the user that he has installed an undersized plug. In such a case the undersized plug must be removed and a larger plug installed correctly.

Plugs were tested in coupons made with elliptical holes that were 0.012 to 0.016 inches out-of-round and the results compared with similar installations in round holes. There was no evidence of leakage. The blow-out test results are shown in Figure 14. This plot shows that blowout pressure was not affected by the out-of-round condition. Furthermore tests with the power brush on a hole, that was 0.0150 inches out-of-round before brushing, showed that the out-of-round condition was reduced to 0.002 inches after 10 seconds of brushing.

Tests were conducted on a mock-up of a tubesheet shown in Figure 15 to determine the stress placed upon adjacent tubes by the installation of a P2 plug. The tubesheet design was per TEMA class R with ligament thickness of 0.180 inches. Tubes were rolled into the six outer holes and the tube to sheet joints were vacuum leak tested using an Expansion Seal Technologies G-650 test gun. All the rolled joints were determined to be leak tight immediately after rolling. Dimensional measurements of the rolled tube ID's were taken with electronic calipers and recorded after the leak test. Strain gages were mounted to the tubesheet face at the narrowest section of the ligaments around the center hole to measure circumferential stress. A P2 plug was installed in the center tubesheet hole which did not have a tube installed. Measurements taken of the six outer tube ID's after the plug installation did not show evidence of any permanent deformation beyond the repeatability capability of the measurement system which was better than 0.0005 inches. The measured strain due to the plug installation was less than 30% of the strain when a tube was rolled into one of the outer holes of the tubesheet mock-up. Furthermore, a vacuum leak test performed on all the tube to tubesheet joints after the plug installation verified that all those joints remained leak tight.

One of the most important tests run on the new design of plug was thermal cycling. The test apparatus is shown in Figure 16. A 2-1/2 inch diameter coupon is surrounded by a band heater. The test plug is installed in the center of the coupon and one side of the plug is exposed to water under pressure. The water temperature and pressure are monitored by a thermocouple and pressure transducer. The band heater was cycled on and off as the water temperature behind the plug dropped to 400°F and rose to 500°F. At the same time water was trapped behind the plug at a pressure that cycled between approximately 5000 and 6000 psi. The rate of temperature rise and fall were respectively 750°F/hr and 240°F/hr. A portion of the temperature and pressure readings are shown in Figure 17. The thermal transients are more severe than would be expected in any base load heat exchanger as the OD of the small coupon experiences 1100°F during the heating portion of the cycles. The plugs were visually monitored for signs of leakage and the test was run for over three hundred cycles. This is considered to be equivalent to about ten months of operation for a base load plant. No sign of leakage was observed during the entire test and the blowout pressures at the end of the test were in excess of 20,000 psi. It may also be significant to note that mechanical plugs of an earlier design showed leakage after less than 50 cycles.

A pressure cycling test was conducted by shocking the plugs with over 100 cycles of 0 to 7000 psi using the set-up in Figure 11. The pressure was cycled between atmospheric and 7000 psi by manually operating the shut-off and bleed valves. This was done rapidly to create a pressure change that is shown if Figure 18. The plugs were monitored for leakage and none was observed. Blowout tests at the conclusion showed no loss of gripping power as the blowouts were in excess of 19,120 psi..

The effect of prolonged service at 650°F was tested in the set-up of Figure 16 where 24 plugs were tested for blowout at intervals of 1 hr, 10 hrs, and 100 hrs. Since creep is known to be a logarithmic function with time under these conditions of loading, the amount of creep for each decade of time would be the same. Therefore, the creep in the first hour would be the same as the creep between 1 hr and 10 hrs, or between 10 hrs and 100 hrs and so forth. If there was any measurable creep rate it would be possible to extrapolate it over longer periods of time in this manner. If the plug were to creep at these temperatures it would be expected to blow out at a lower pressure which was not the case as seen by the data in Figure 19. It appeared that prolonged service at this temperature actually increased the holding power of the plug.

Vibration tests were run using the test-set-up of Figure 20. The plugs were subjected to vibrations of 3g's at a frequency of 120hz while being subjected to a pressure difference of 7000 psi. There was no sign of leakage during the 13 hour test. Although this test was relatively short because of the noise generated and the large demand on our air supply, it was significant that there was no noticeable reduction in the blowout pressure of the plugs that had experienced this level of vibration.

Field Experience

The new design plug was first installed in April of 1994 in high pressure heat exchangers in a southern New Jersey fossil power plant. These plugs have continued to perform flawlessly to this date. From the time of this initial field test many thousands of plugs have been installed in heat exchangers in North America, Europe and Asia with excellent results. The new design plugs have also been installed in supercritical plants.

The Davis-Besse Nuclear Power Station heat exchangers, manufactured by Westinghouse Electric Corporation, have working temperatures of 500°F and pressures of 1500 psi. Davis-Besse calculates they saved over $5,000 in the first installation of 290 P2 plugs as opposed to using welded plugs.

Substantial cost savings have been obtained by other users of Pop-A-Plugs®. Navajo Generating Station, Salt River Project, performed a study comparing the cost of installing Pop-A-Plugs® versus explosive plugs[3]. They achieved savings of $34,000 by installing 200 Pop-A-Plugs® instead of explosive plugs. Additionally they saved 6 1/2 days of downtime and avoided damage to the heat exchanger.

Levon Strickland, Engineer in charge of Feedwater heaters and Condensers at Santee Cooper, says their average cost of using explosive plugs is $6000 per incident[4]. He determined they saved between $4500 to 5000 per leakage incident by using Pop-A-Plugs. That is a saving of over 75%. Santee Cooper is the largest fossil plant in South Carolina.

Eddystone Generating Station of PECO Energy installed 14 Pop-A-Plugs® during an outage in March of 1995 instead of their normal practice of using explosive plugs[5]. John Hugues, PECO Maintenance Planner, calculated savings of $3,300 for just 7 tubes.

Acknowledgements

Many associates made important contributions to the development of the P2 Pop-A-Plug. Eugene Cunningham contributed the key idea of internal serrations that solved some difficult problems. Jim Berneski was responsible for many of the ideas and development of the tube preparation method. Henry Brandenburger also made valued contributions to the program. Glenn Craig and Jim Berneski did much of the testing.

References

1. US Patent number 4,425,943
2. US Patent number 5,437,310
3. Navajo Generating Station internal document
4. “Field Notes” in September 1993 edition of *Power Engineering*
5. Eddystone Generating Station internal memo dated 3/29/95

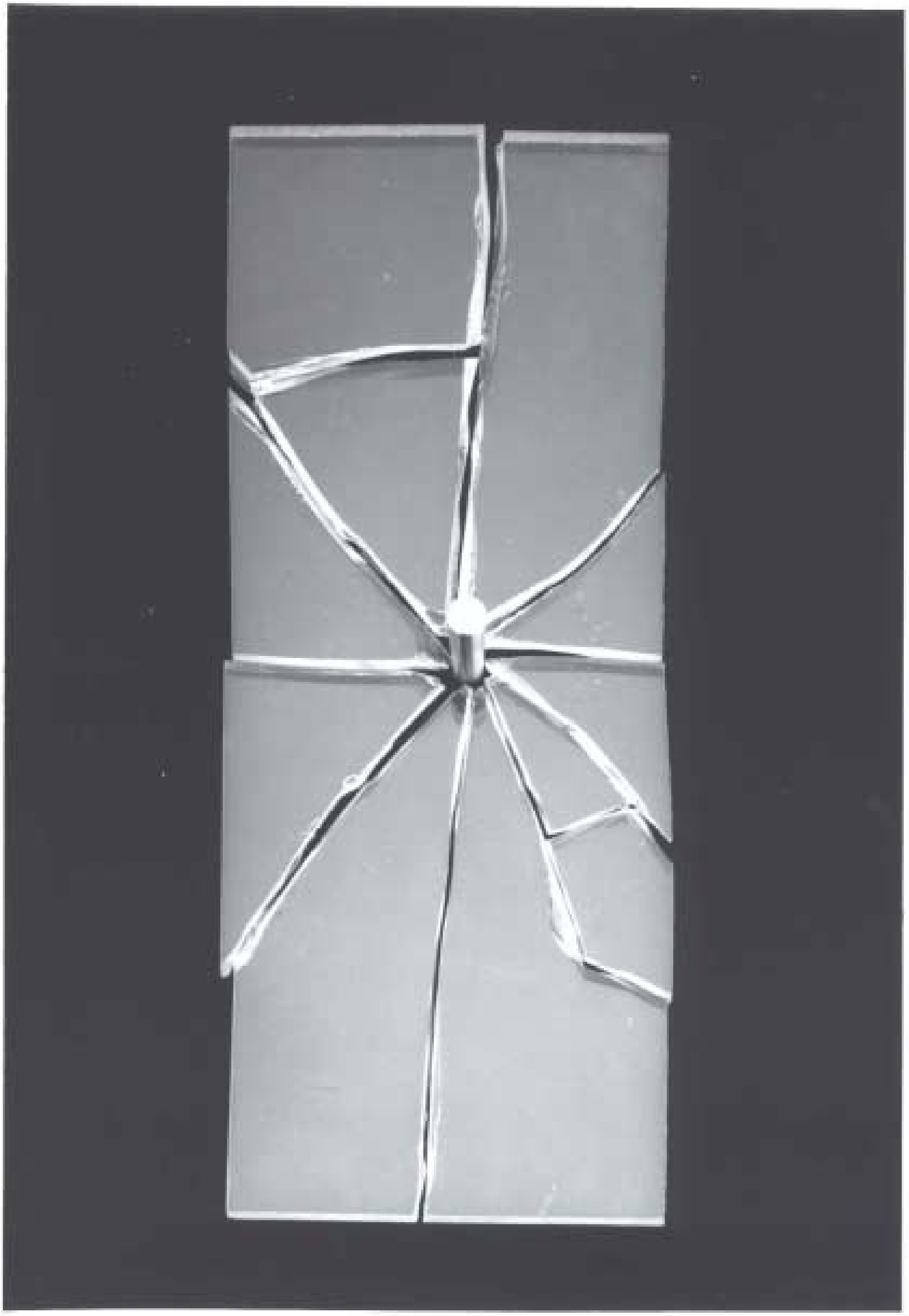


Figure 1

OLD STYLE PRP POP-A-PLUG

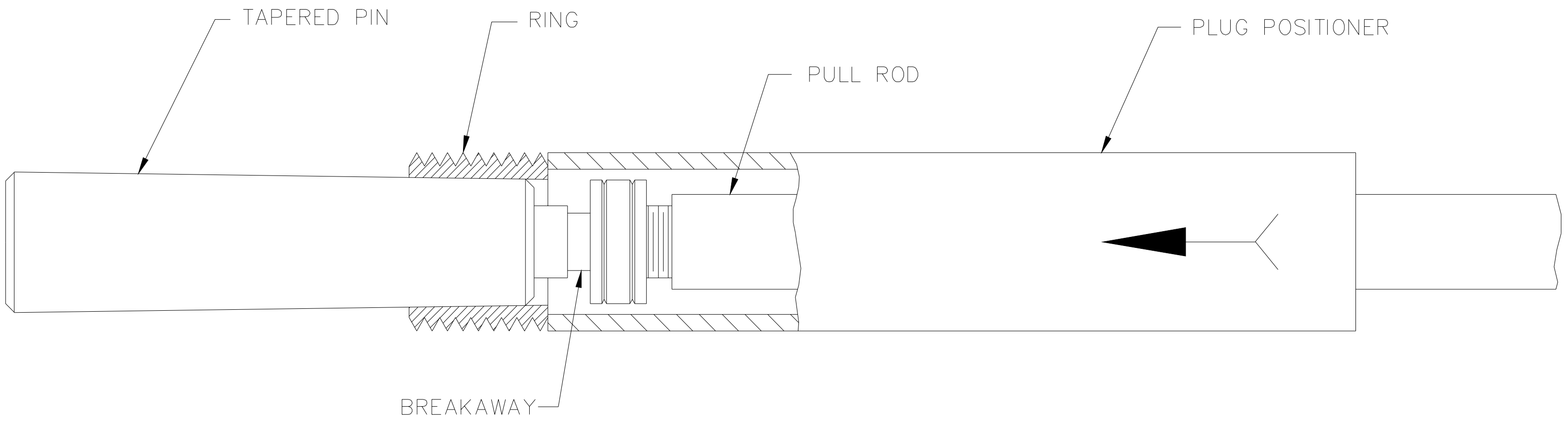


FIGURE 2

SIMPLE METHOD FOR DETERMINING TUBE SIZE

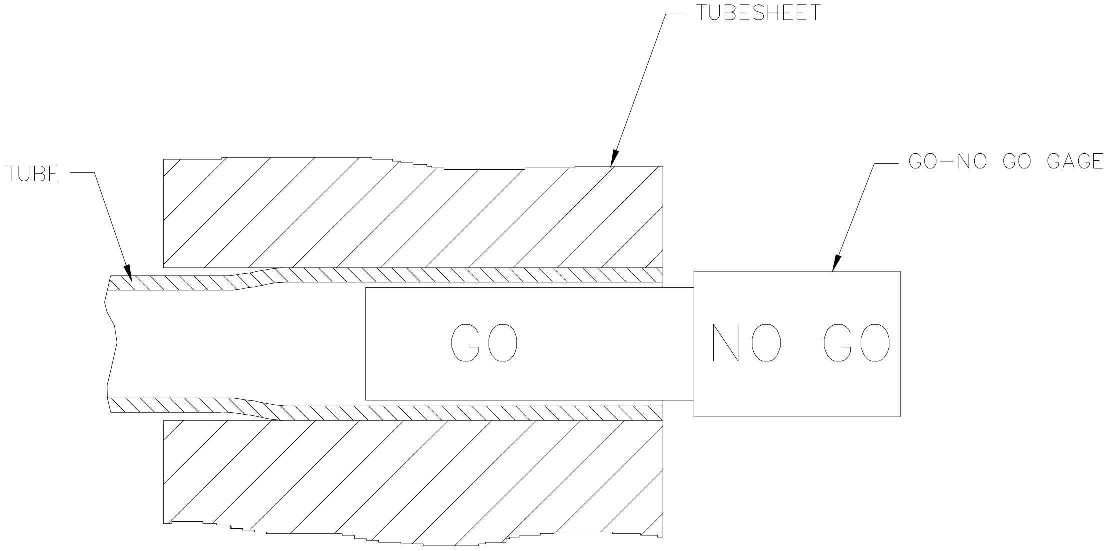


FIGURE 3

TUBE INLET EROSION

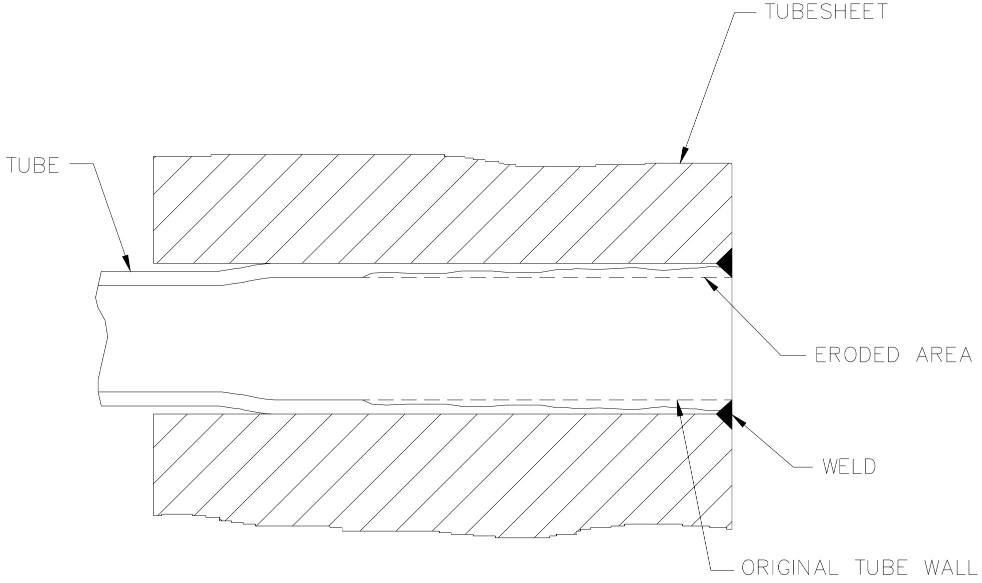


FIGURE 4

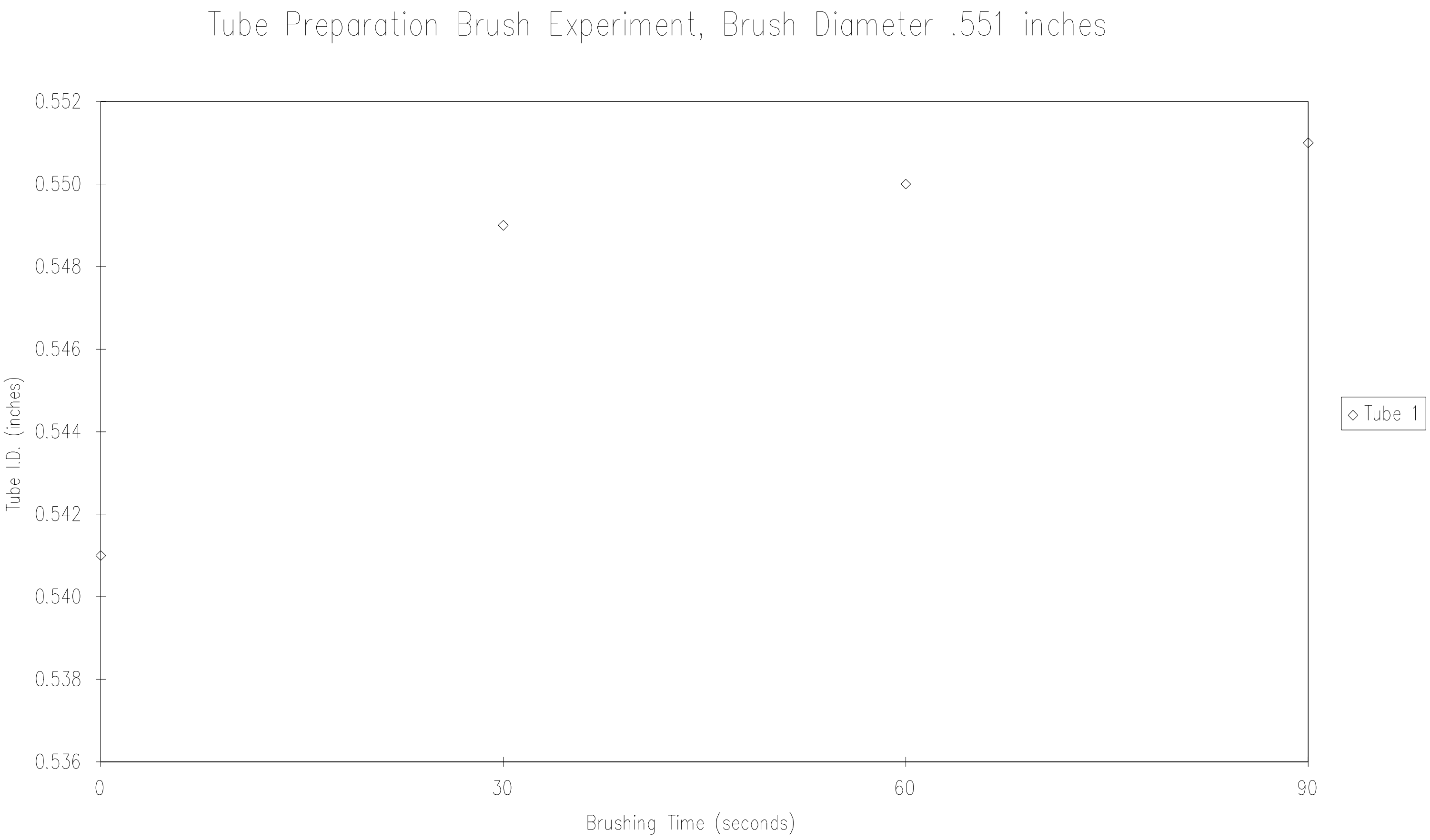

Tube Preparation Brush Experiment, Brush Diameter .551 inches
Tube I.D. (inches)
0.552
0.550
0.548
0.546
0.544
0.542
0.540
0.538
0.536
0
30
60
90
Brushing Time (seconds)
◇ Tube 1

FIGURE 5

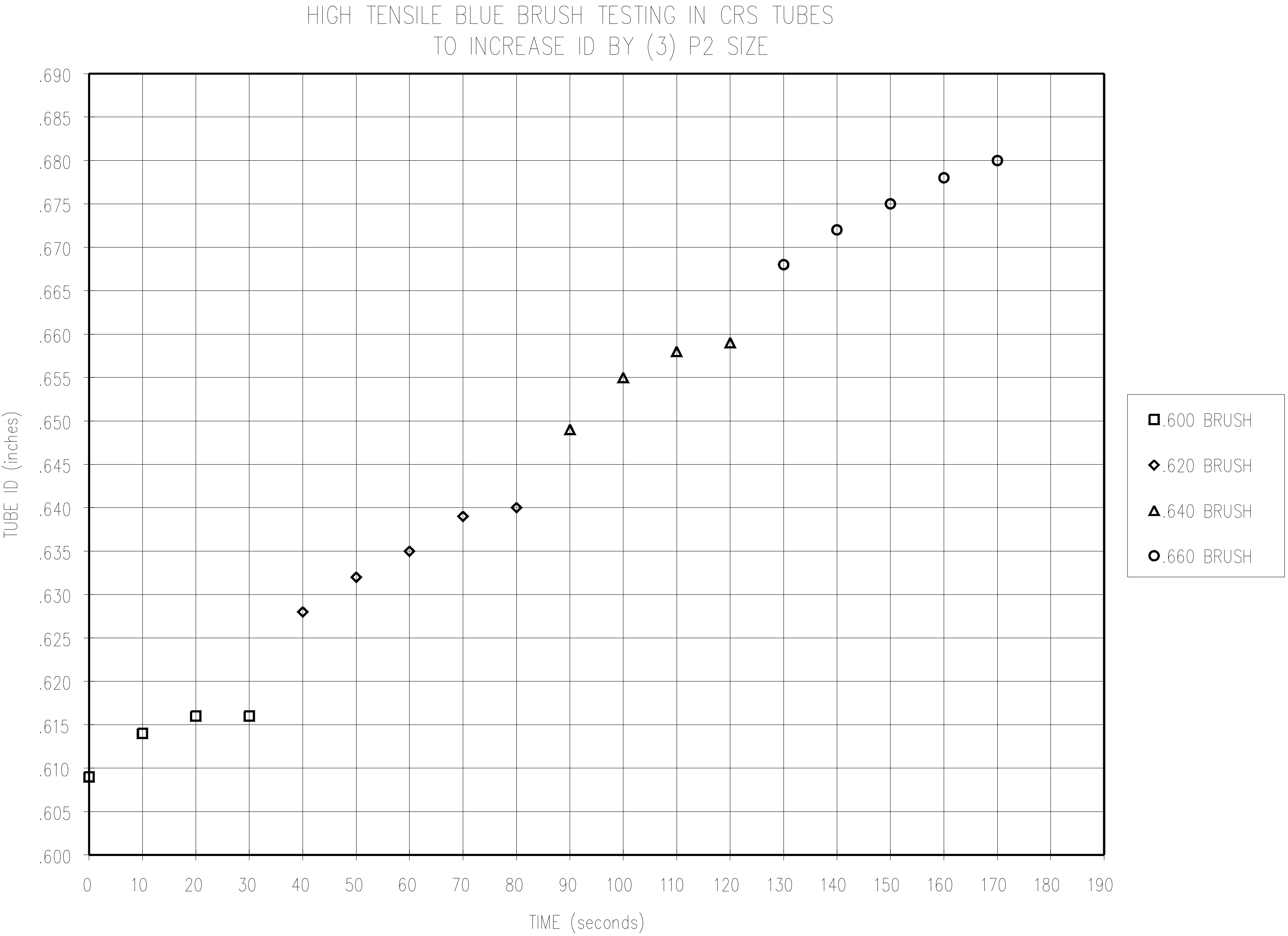

HIGH TENSILE BLUE BRUSH TESTING IN CRS TUBES
TO INCREASE ID BY (3) P2 SIZE
TUBE ID (inches)
.690
.685
.680
.675
.670
.665
.660
.655
.650
.645
.640
.635
.630
.625
.620
.615
.610
.605
.600
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
TIME (seconds)
□ .600 BRUSH
◇ .620 BRUSH
△ .640 BRUSH
○ .660 BRUSH

FIGURE 6

DEVELOPMENT TEST APPARATUS

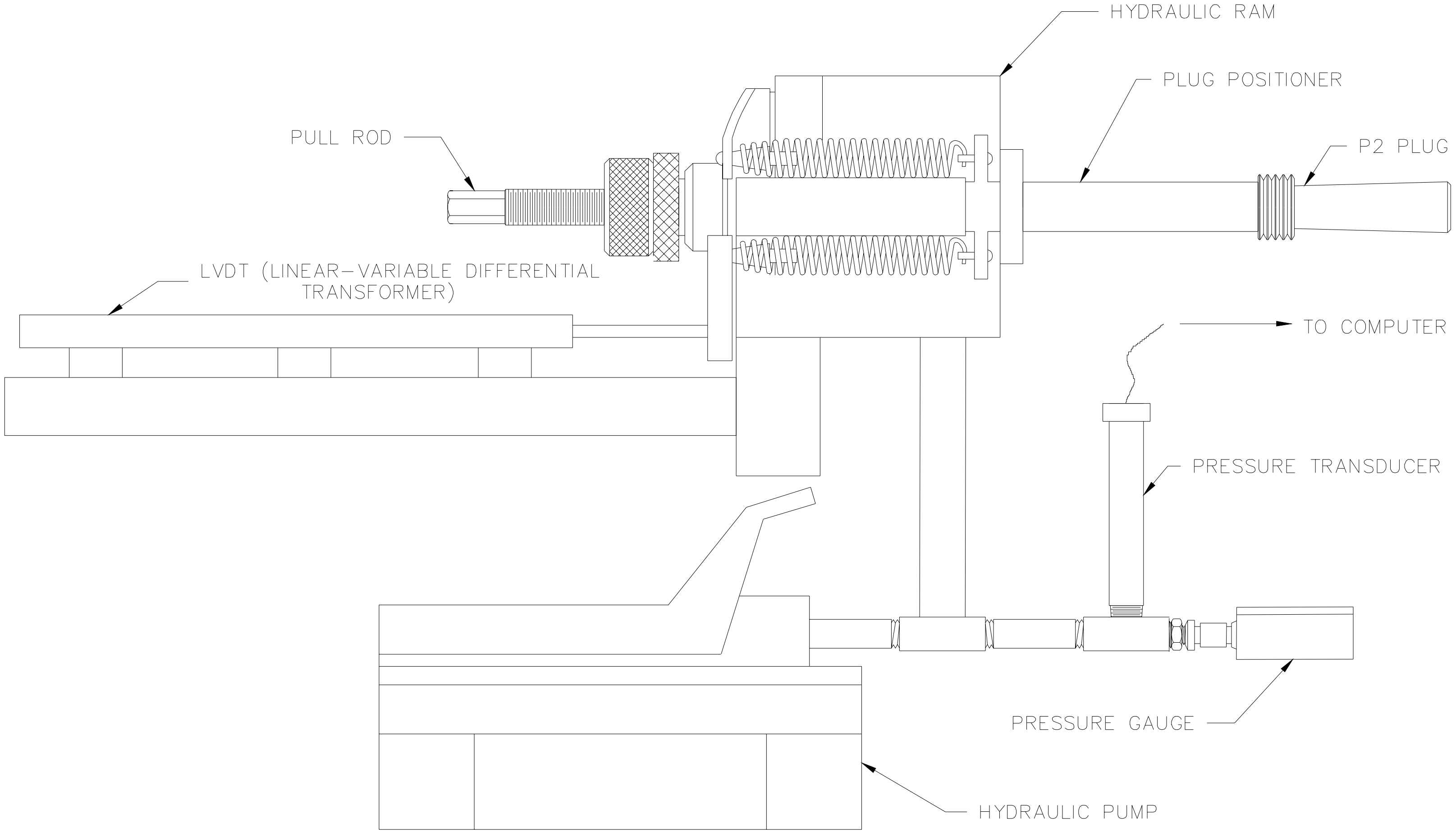
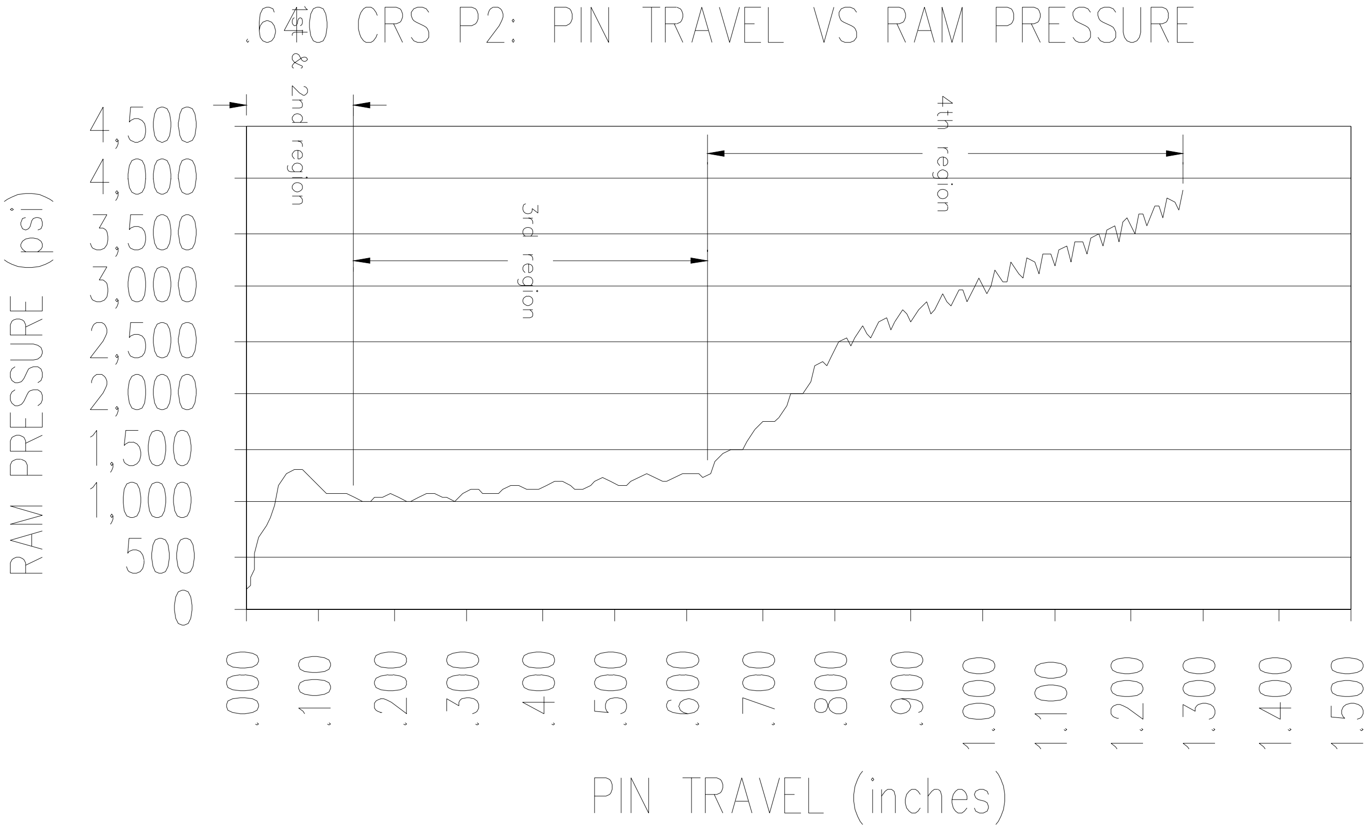


FIGURE 7



.640 CRS P2: PIN TRAVEL VS RAM PRESSURE

FIGURE 8A

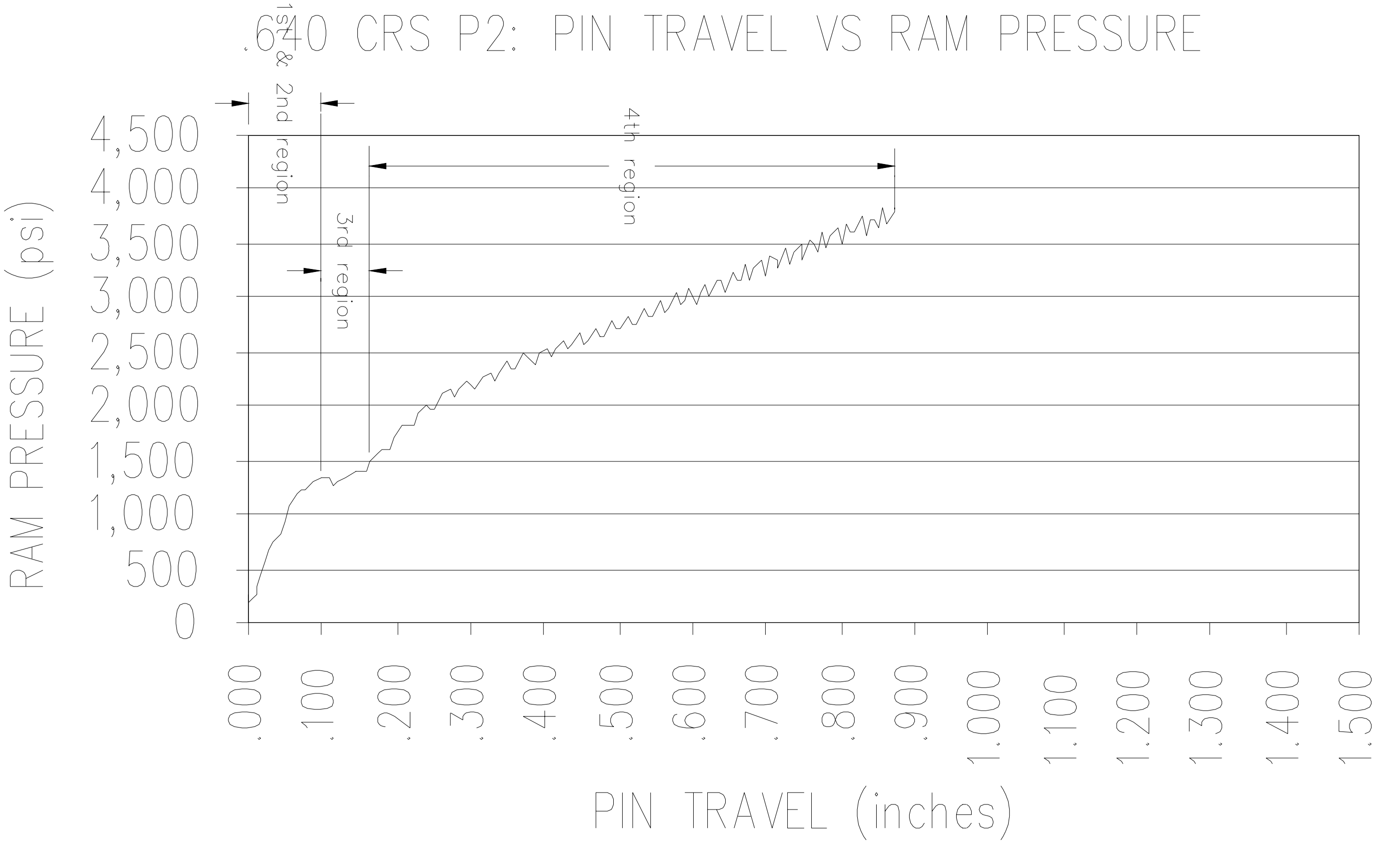

.640 CRS P2: PIN TRAVEL VS RAM PRESSURE
1st & 2nd region
3rd region
4th region
RAM PRESSURE (psi)
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
.000
.100
.200
.300
.400
.500
.600
.700
.800
.900
1.000
1.100
1.200
1.300
1.400
1.500
PIN TRAVEL (inches)

FIGURE 8B

NEW P2 POP-A-PLUG DESIGN

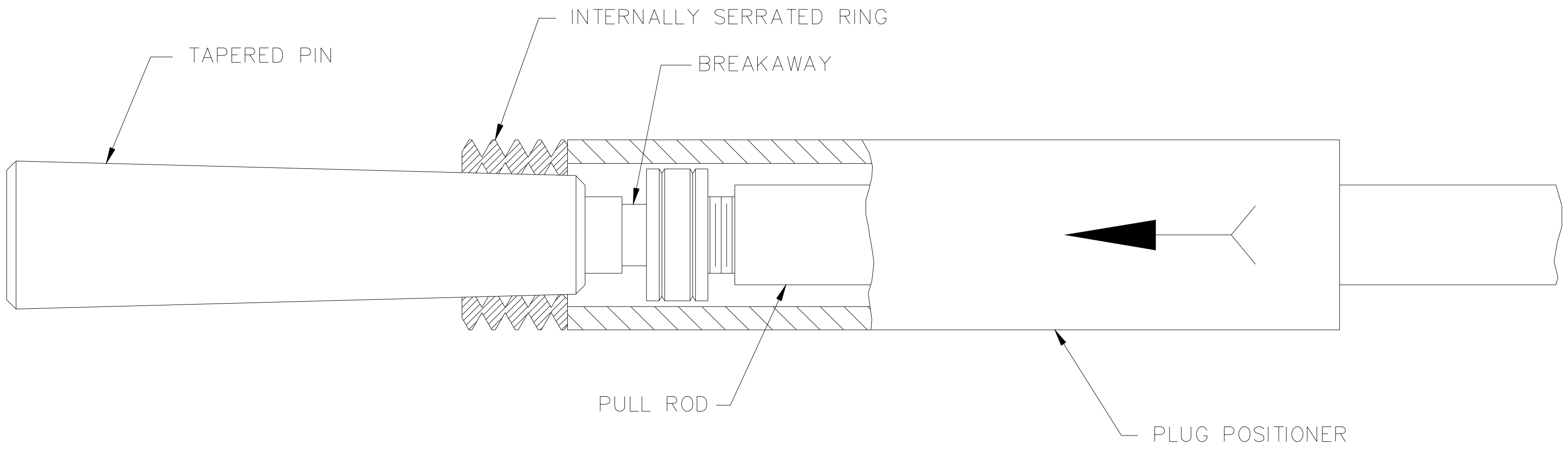


FIGURE 9

HELIUM LEAK TEST SET-UP

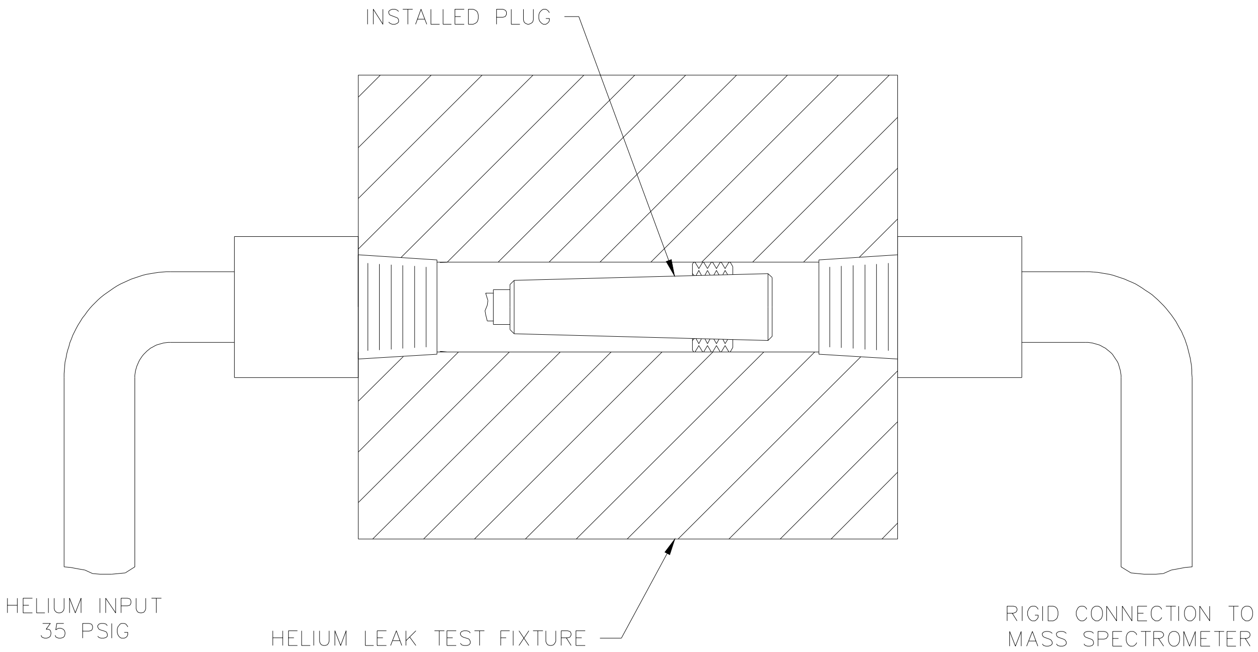


FIGURE 10

BLOW-OUT TEST SET-UP

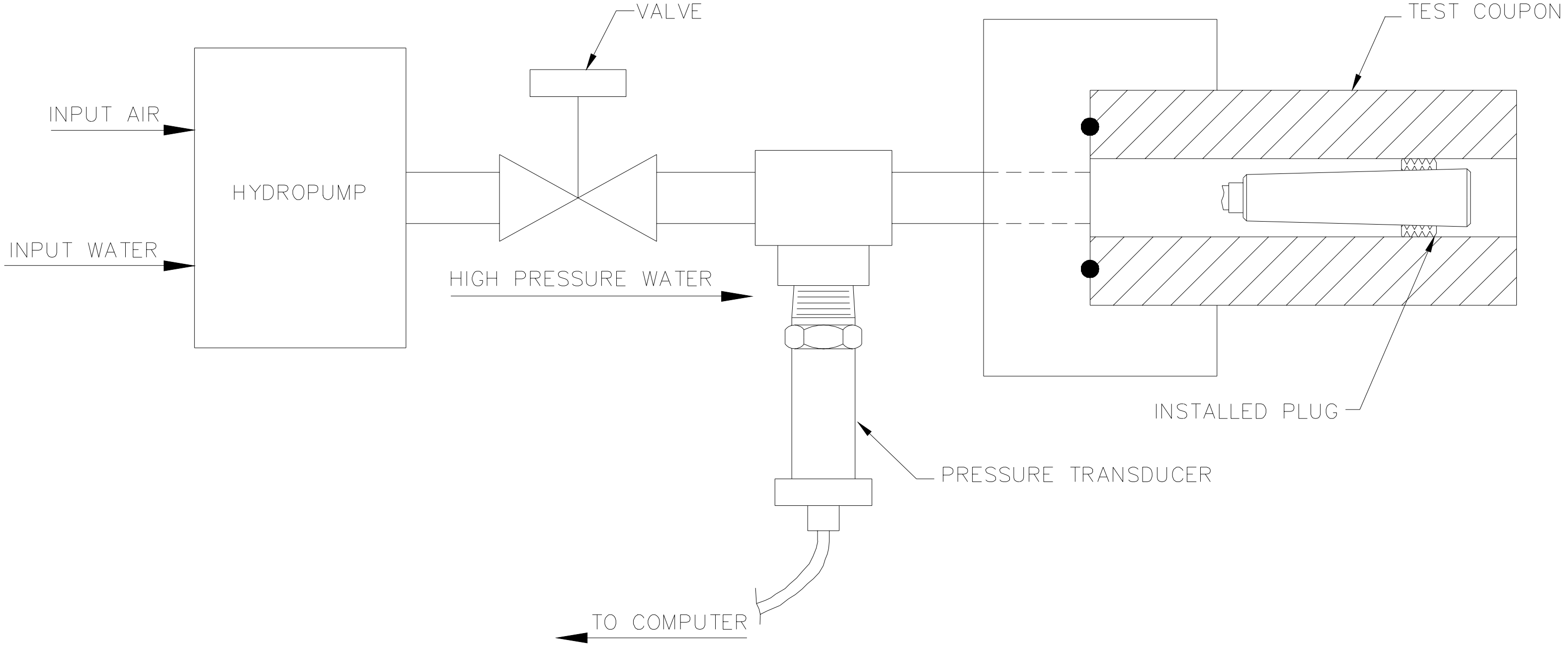


FIGURE 11

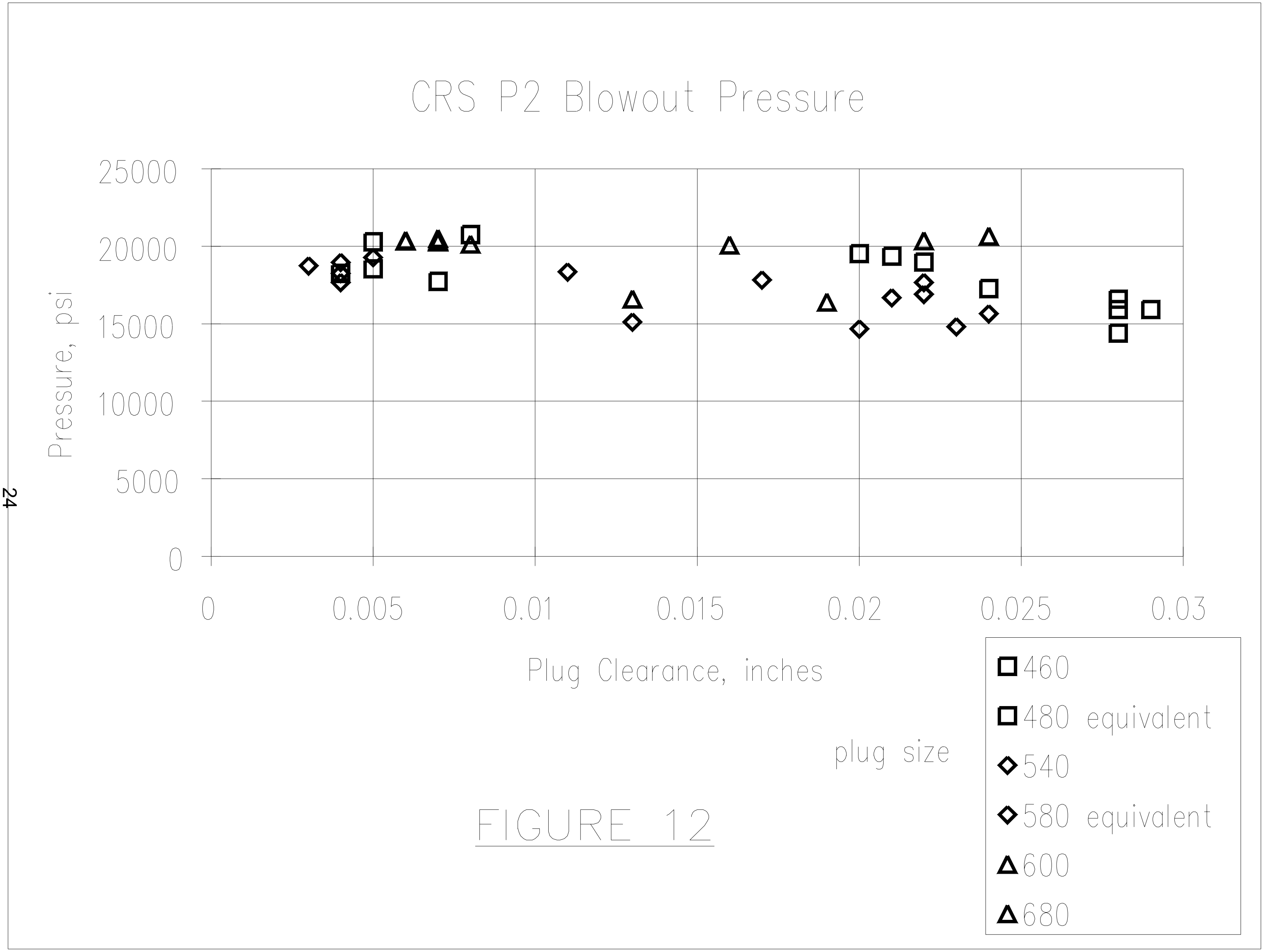
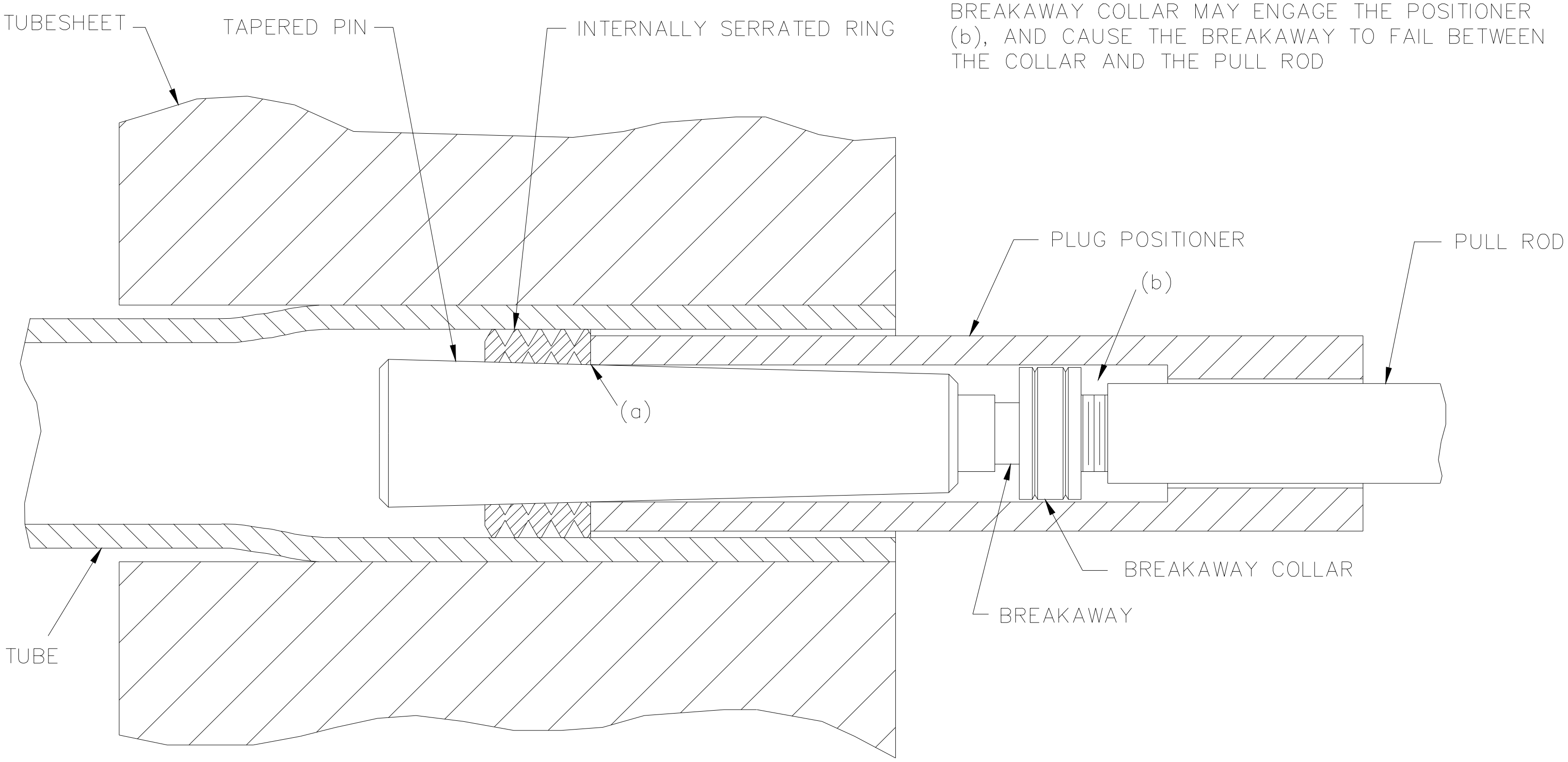

CRS P2 Blowout Pressure
25000
20000
15000
10000
5000
0
Pressure, psi
0
0.005
0.01
0.015
0.02
0.025
0.03
Plug Clearance, inches
plug size
□ 460
□ 480 equivalent
◇ 540
◇ 580 equivalent
△ 600
△ 680

FIGURE 12

INSTALLATION OF UNDERSIZED PLUG



THE POSITIONER WILL CATCH ON THE PIN (a),
IF THE PLUG IS UNDERSIZE. IN ADDITION, THE
BREAKAWAY COLLAR MAY ENGAGE THE POSITIONER
(b), AND CAUSE THE BREAKAWAY TO FAIL BETWEEN
THE COLLAR AND THE PULL ROD

FIGURE 13

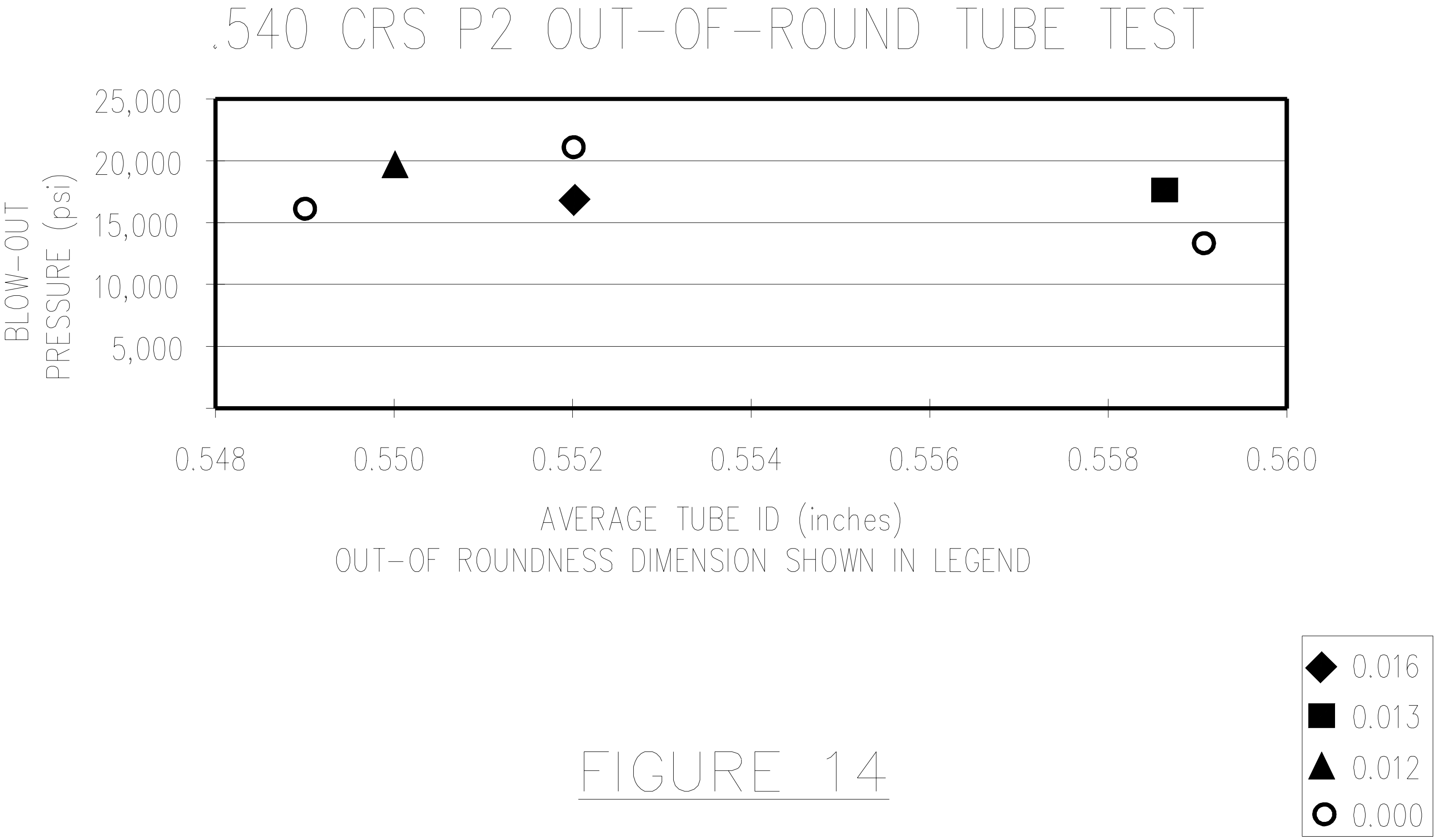

.540 CRS P2 OUT-OF-ROUND TUBE TEST
BLOW-OUT PRESSURE (psi)
25,000
20,000
15,000
10,000
5,000
0.548
0.550
0.552
0.554
0.556
0.558
0.560
AVERAGE TUBE ID (inches)
OUT-OF ROUNDNESS DIMENSION SHOWN IN LEGEND
◆ 0.016
■ 0.013
▲ 0.012
○ 0.000

FIGURE 14

TUBESHEET MOCK-UP PER TEMA CLASS R

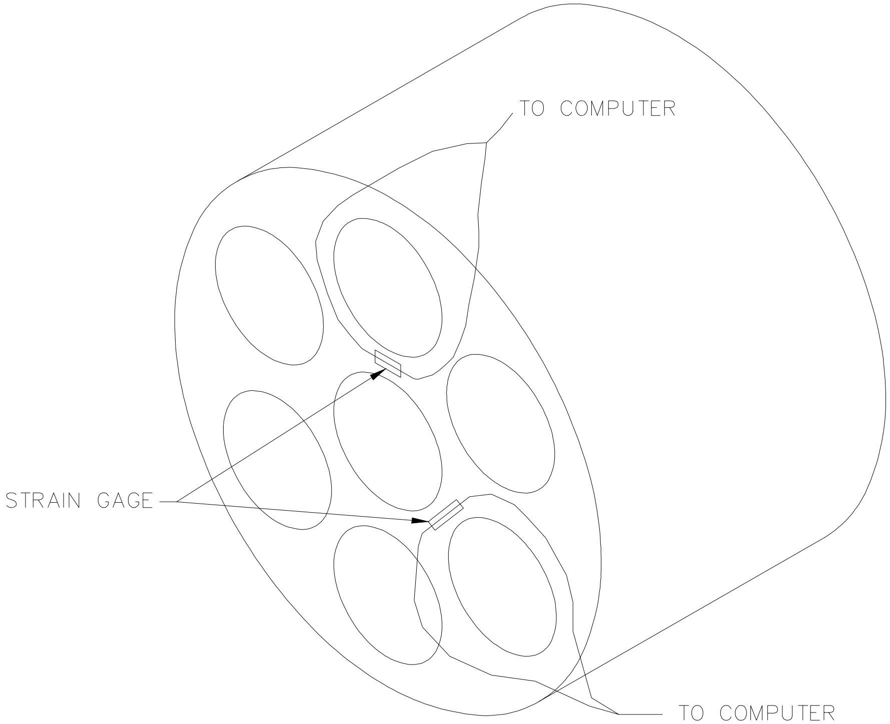


FIGURE 15

THERMAL CYCLE TEST SET-UP

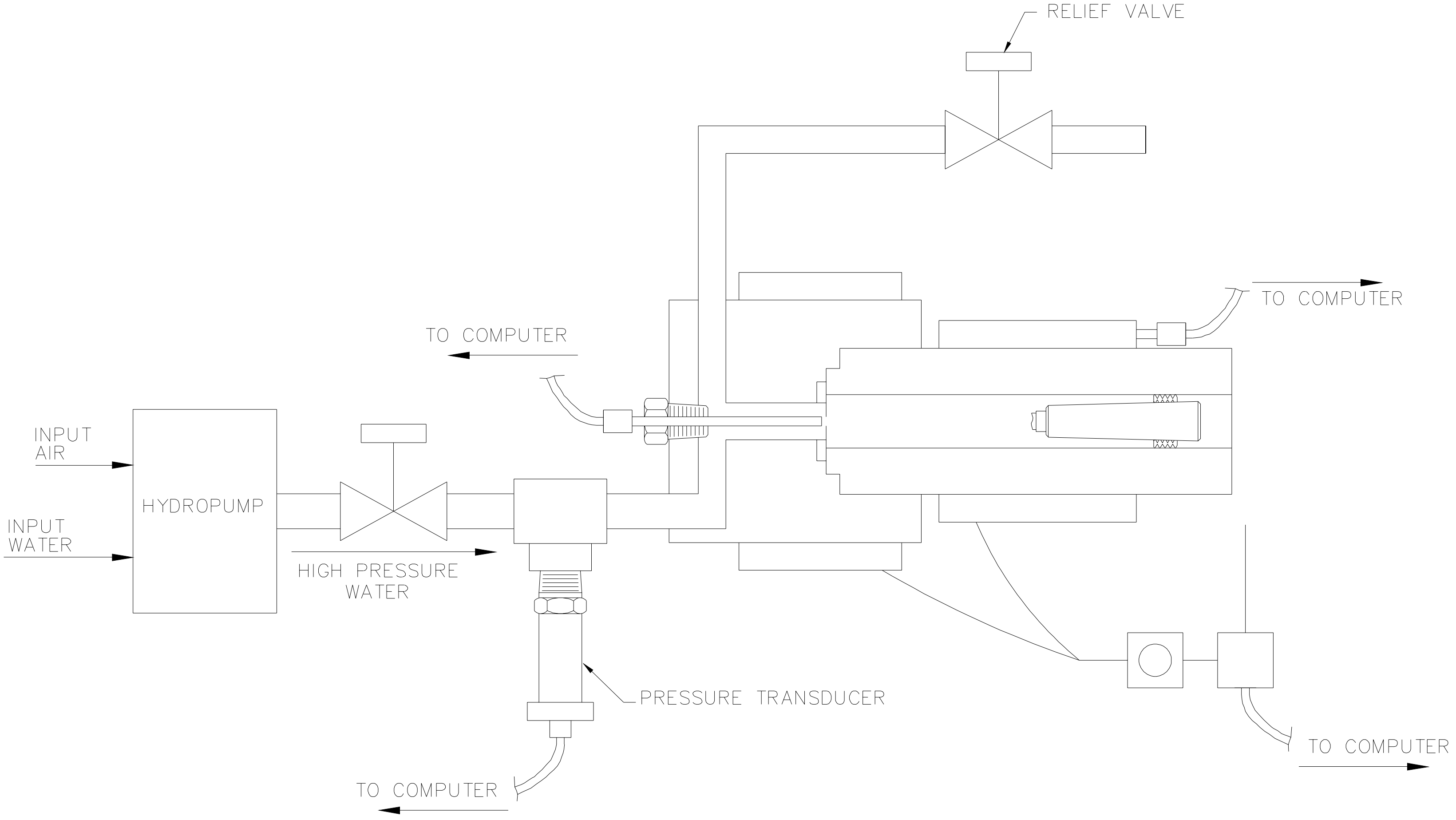


FIGURE 16

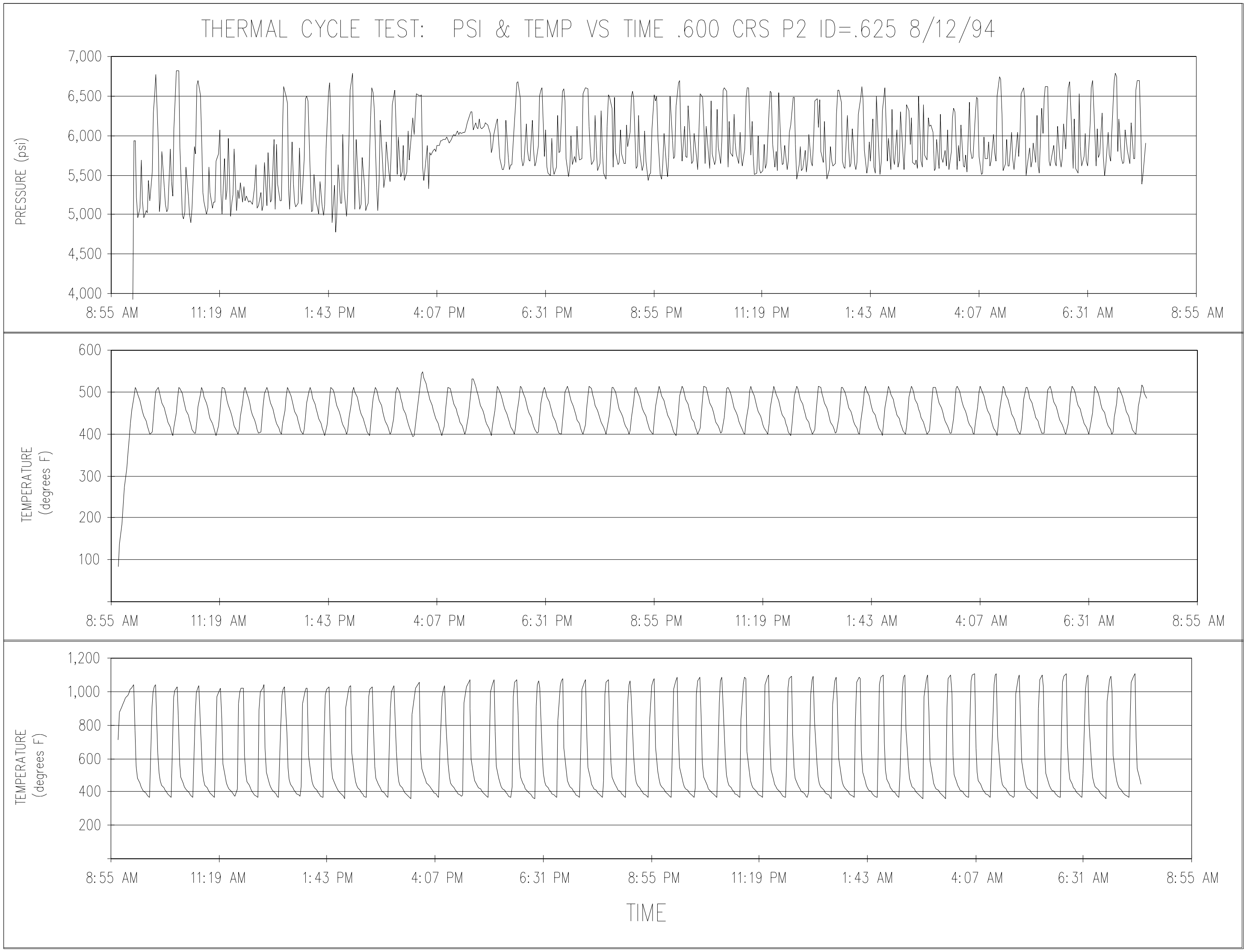

THERMAL CYCLE TEST: PSI & TEMP VS TIME .600 CRS P2 ID=.625 8/12/94
PRESSURE (psi)
7,000
6,500
6,000
5,500
5,000
4,500
4,000
TEMPERATURE (degrees F)
600
500
400
300
200
100
TEMPERATURE (degrees F)
1,200
1,000
800
600
400
200
8:55 AM
11:19 AM
1:43 PM
4:07 PM
6:31 PM
8:55 PM
11:19 PM
1:43 AM
4:07 AM
6:31 AM
8:55 AM
TIME

FIGURE 17

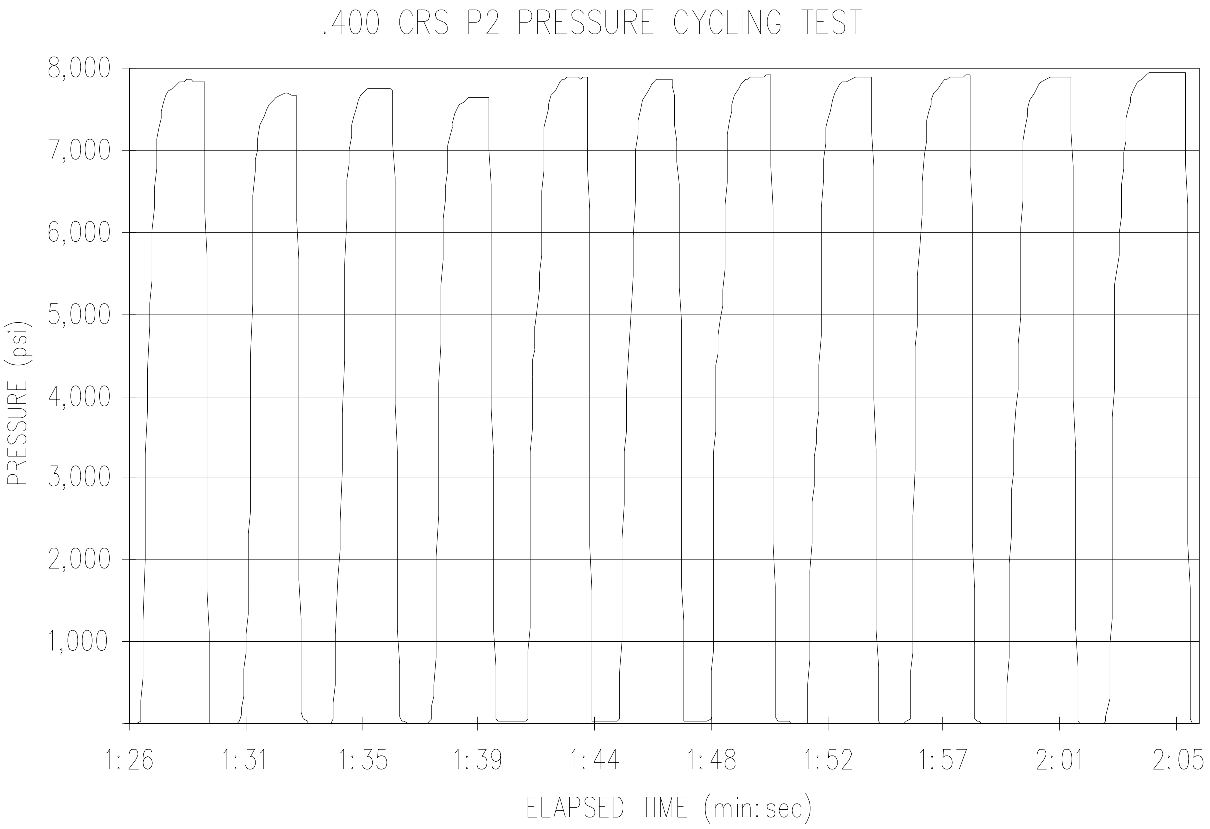

.400 CRS P2 PRESSURE CYCLING TEST
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
PRESSURE (psi)
1:26
1:31
1:35
1:39
1:44
1:48
1:52
1:57
2:01
2:05
ELAPSED TIME (min:sec)

FIGURE 18

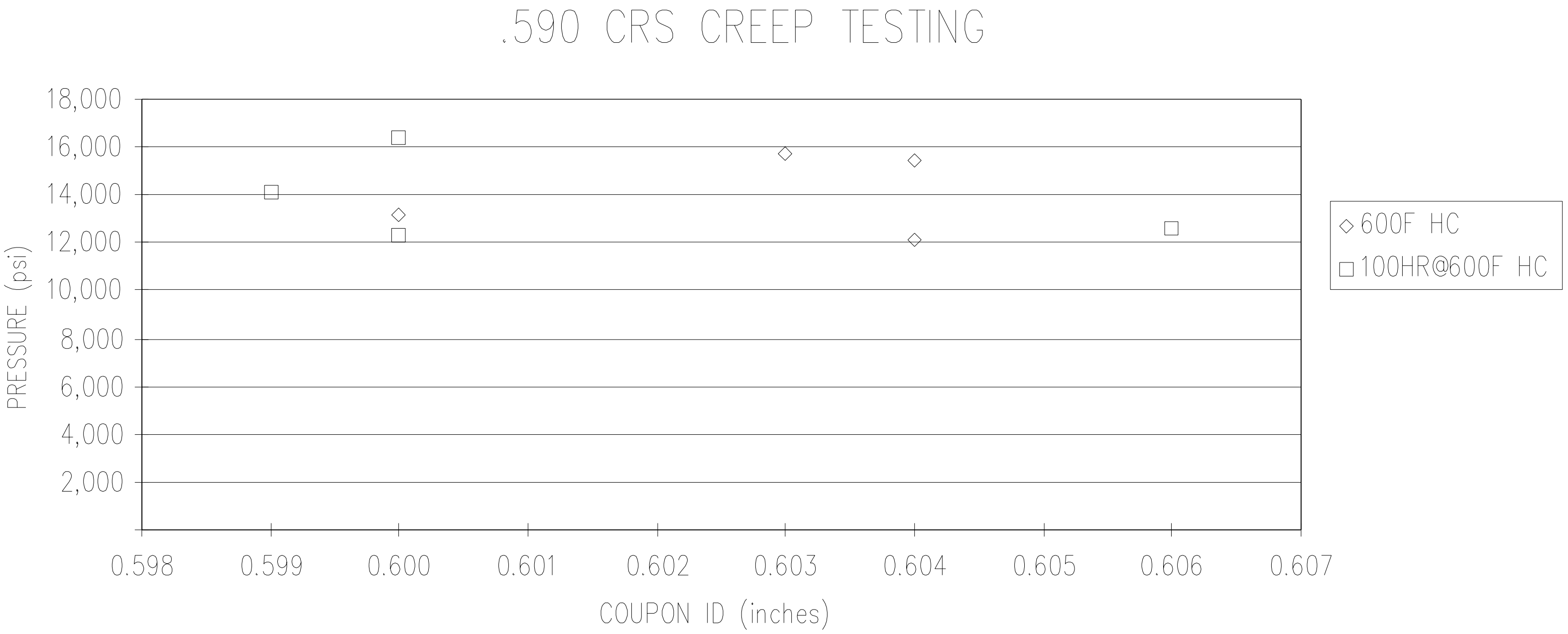

.590 CRS CREEP TESTING
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
PRESSURE (psi)
0.598
0.599
0.600
0.601
0.602
0.603
0.604
0.605
0.606
0.607
COUPON ID (inches)
◇ 600F HC
□ 100HR@600F HC

FIGURE 19

VIBRATION TEST SET-UP

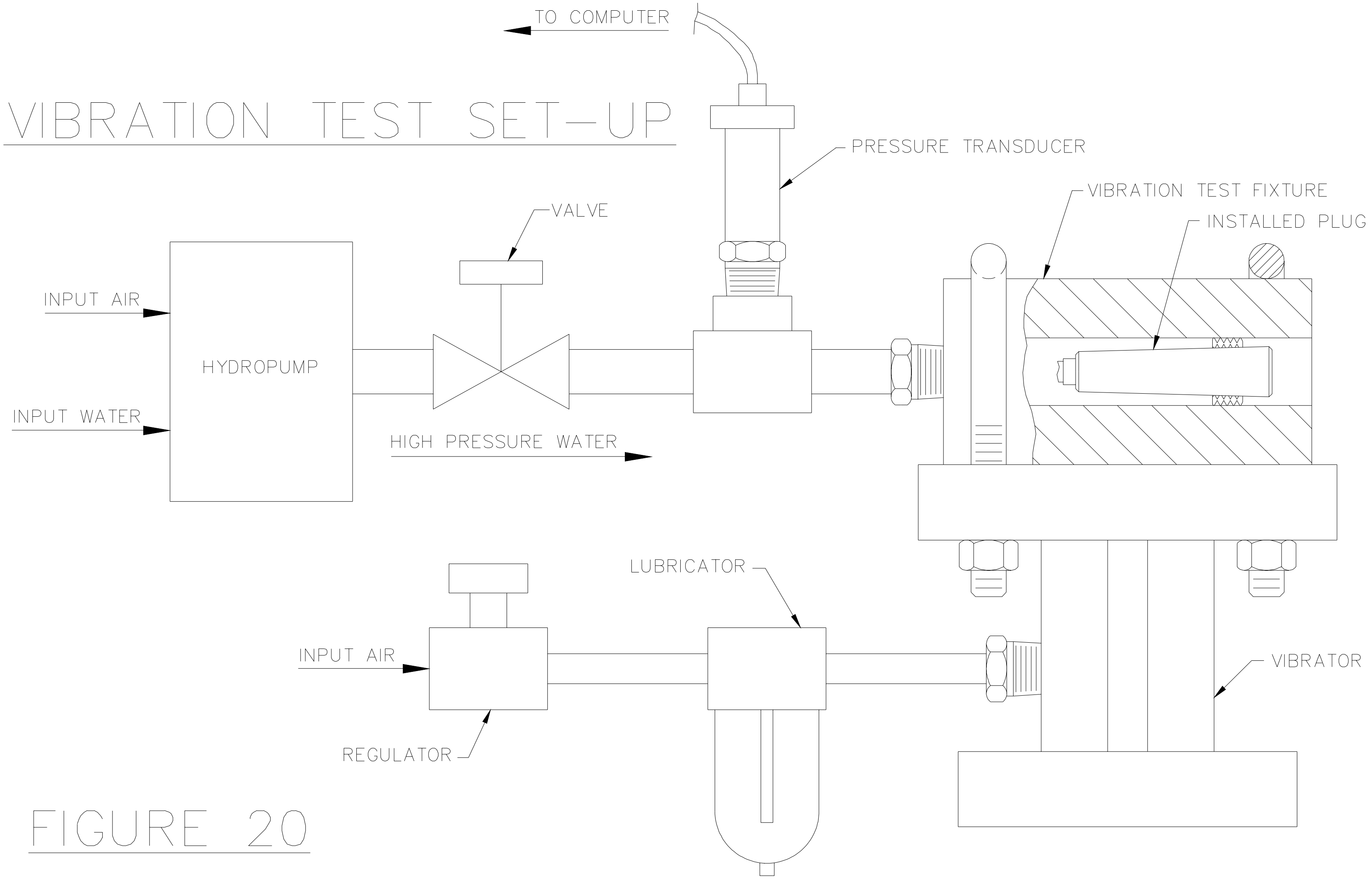


FIGURE 20